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Project Summary

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Flux Force/Condensation Scrubbing for Collecting Fine Particulate from Iron Melting Cupolas

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A flux force/condensation (F/C) scrubbing system for controlling particulate emissions from an iron and steel melting cupola demonstrated its industrial feasibility during a 6-month test period.

A particle collection efficiency of 84 percent was required to meet the emission limit for a melting rate which ranged around 12,500 kg/hr. The demonstration plant was designed to enable experimental determination of operating characteristics when attaining efficiencies around the emission limit. Particle size distributions, flow rates, pressure drops, temperatures, and other parameters were measured and utilized for performance analysis and comparison with theoretical predictions.

After an initial period during which equipment and operating methods were refined, the system performed well and without significant difficulty. An optimized F/C scrubbing system for this application would require only about 65 percent of the predicted power requirement for a conventional high energy system.

This Project Summary was developed by EPA's Industrial Environmental Research Laboratory, Research Triangle Park, NC, to announce key findings of the research project that is fully documented in a separate report of the same title (see Project Report ordering information at back).

Introduction

Flux force/condensation (F/C) scrubbing has been developed by Air Pollution Technology, Inc. under EPA-sponsorship for the past several years (see Table 1). The object of F/C scrubbing is to reduce the power requirement for collection of fine particles as compared to conventional high energy scrubbers. The improvement in scrubber performance due to condensation effects is most apparent in the submicron size range where the mechanism of inertial impaction is difficult to apply economically. Water vapor from a hot saturated gas can be condensed by contacting the gas with cold liquid.

Three condensation effects are utilized in F/C scrubbing. The suspended particles in the gas act as condensation nuclei, resulting in growth of particle mass due to the condensation of water vapor. The transfer of water vapor toward the cold liquid results in diffusiophoresis, causing particles to collect by movement of the condensing vapor toward the cold surface. Simultaneously, the temperature gradient established in the condenser creates a thermal force which leads to collection

by thermophoresis. The three effects enhance the particle collection efficiency of the F/C scrubber system.

Background

Flux force effects on particles have been known for many years, and the background has been reviewed and discussed in depth by many authors. The research and development work supported by the EPA was aimed at first assessing the potential of F/C scrubbing, then developing rational means for exploiting it, and then demonstrating the technology.

The feasibility of F/C scrubbing and a rational design basis were established in the first four studies listed in Table 1. The next step was a pilot-scale demonstration, carried out on a secondary metal recovery furnace. Control of the entire source effluent, a maximum flow rate of 200 Am^3/min (7,000 acfm) at temperatures up to 800°C, required both particle collection and acid gas absorption. Demonstration plant performance was consistent with the preceding laboratory, bench scale, and pilot-plant studies.

Earlier studies (see Table 1) included theoretical development of design equations for F/C scrubbing and the development of a computerized mathematical model to predict particle collection in a sieve plate F/C scrubber. The predictions compared well with experimental results, but the computerized model was cumbersome. In the first demonstration study, a revised mathematical model was developed from the same basic relationships, and the design procedures were greatly simplified for prediction of F/C scrubber performance.

This report gives results of a demonstration project to test further the design methods and economics of F/C scrubbing on a large scale in an industrial environment. An F/C system for the total exhaust gas stream form a 12,500 kg/hr iron melting cupola was designed, built, and tested. The operating experience included summer, fall, and winter in a demanding environment and resulted in a good test of equipment design and materials selection.

System Design

As a replacement system in an operating plant, the F/C scrubber had to fit in the space around the existing scrubber system. Once the new apparatus was in place, it had to be connected and the old system disconnected with the minimum loss of productive operation of the cupola. This and the space constraints imposed by the foundry operations had the major influence on F/C system layout.

Conservation of project cost required that the maximum amount of existing auxiliary equipment be used. Thus, the existing afterburner, scrubber pump and sump, fan, and stack were used.

The F/C system was built to operate in two basic configurations, induced draft (I.D.) and forced draft (F.D.). The F.D. mode has the potential advantage of reducing the fan power requirement by about 6 percent, with the possible disadvantage of entrained liquid entering the fan.

The system flow diagram in Figure 1 is for the I.D. configuration. Only the ducting was modified to switch from F.D. to I.D.; the remaining components remained unchanged.

Table 1. F/C Scrubbing Studies by A.P.T. for EPA

Title	Subject
Wet Scrubber System Study — "Scrubber Handbook" (Vol. I), Report EPA-R2-72-118a (NTIS PB 213-016), August 1972	*F/C scrubbing principles and potential.*
Feasibility of Flux Force/Condensation Scrubbing for Fine Particulate Collection, Report EPA-650/2-73-036 (NTIS PB 227-307), October 1973	*Theoretical analysis, mathematical modeling, computer prediction, experimental data from bench-scale F/C scrubbers.*
Study of Flux Force/Condensation Scrubbing of Fine Particles, Report EPA-600/2-75-018 (NTIS PB 249-297), August 1975	*Laboratory pilot-plant study of F/C scrubbing in sieve plate and spray apparatus.*
Study of Horizontal-Spray Flux Force/Condensation Scrubber, Report EPA - 600/2-76-200 (NTIS PB 262-669), July 1976	*Laboratory pilot-plant study of F/C scrubbing in horizontal-spray apparatus.*
Fine Particle Collection by Flux Force/Condensation Scrubber: Pilot Demonstration, Report EPA-600/2-77-238 (NTIS PB 277-075), December 1977	*Pilot demonstration of F/C scrubbing with a sieve plate column on a secondary metal recovery furnace, analysis of results, and further development of mathematical modeling.*

Process Description

The cupola melts scrap iron and steel using heat generated by the combustion of coke. Raw materials (when the program started) were scrap structural steel, engine blocks, metal stampings and turnings, cast iron piping and fittings, and other miscellaneous metal parts. During the construction period, the cupola was converted to water cooled operation and the metal charge was changed to small steel scrap.

The scrap and coke are charged together in 1,800 kg batches with an iron-to-coke mass ratio of 6. Small amounts of limestone, 20-30 kg, are also charged to form slag. The nominal rate is 12,500 kg/hr and the normal tuyere air flow rate is 3.5 DNm^3/s.

The exhaust gas from the bed of material in the cupola is composed typically of 14 percent CO, 13 percent CO_2, and 73 percent N_2. Additional combustion air, entering the charging door 2.3 DNm^3/s, allows for complete conversion of CO to CO_2. An ignition burner ensures that a flame source is available for combustion of the CO to CO_2. (It was not needed or used during initial tests.)

Combustion is completed in a brick-lined afterburner. The exhaust gases should leave the afterburner tank at a temperature of 800-1,000°C. The exhaust gas flow rate at this point is about 6.6 DNm^3/s. After the cupola modification and the change to steel scrap charge, the cupola gas would not burn consistently, so the gas temperature was lower and more variable than in preliminary tests.

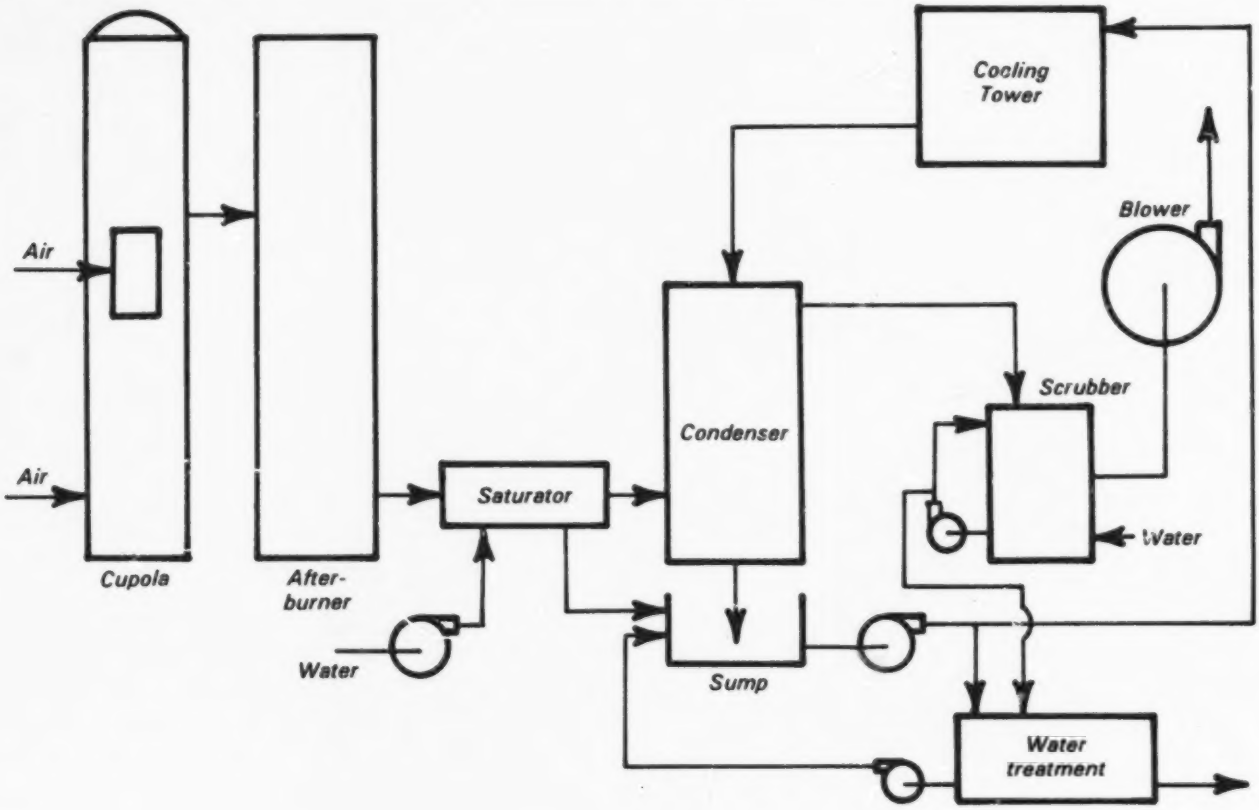

Figure 1. F/C demonstration plant flow diagram, induced draft.

The hot gas leaves the afterburner and is cooled in the saturator by water sprays to a temperature approaching adiabatic saturation. Typically, the saturation temperature was 71 — 77°C. The maximum water spray rate in the saturator is 4.5 l/s (75 gpm).

The condenser and cooling tower system has a design heat rejection rate of 9.6 x 10^6 J/s (33 x 10^6 Btu/hr). The water flow rate can be varied up to 69 l/s (1,100 gpm). The cold gas temperature leaving the counter-current packed-bed condenser is about 55°C at design flow rates.

The exhaust gases leave the condenser and enter either the exhaust fan or the scrubber, depending on the ducting. The primary particle collection device in the system is a gas-atomized scrubber with a variable-area throat, an integral water sump, and an entrainment separator.

The fan used in the demonstration plant was rebuilt from that used in the previous system and is a straight radial blade design. The flow rate of the fan is approximately 14 Am^3/s (30,000 cfm) at -96 cm W.C. (-38 in. W.C.).

The condenser water comes from the cooling tower, designed to cool 69 l/s (1,100 gpm) of water from 66 to 38°C with ambient air. This is accomplished by evaporative cooling.

The settler was designed to remove particles collected by the scrubbing liquid. A 1.3-l/s (20-gpm) stream of sump water is clarified by the settler. The thickened sludge (10-30 percent by wt) is disposed of as landfill. The clarified water (100 ppm solids) is returned to the sump.

Performance Testing

In the course of system start-up, a significant problem with the original exhaust fan caused excessive power consumption and tripping of the electrical overload device. This condition continued until a new A.P.T.-designed fan wheel was installed. Some problems due to foaming and entrainment carryover had to be resolved, but system operation was otherwise quite good during the testing. No production time was lost by the foundry due to problems associated with the operation of the F/C scrubber system.

The major test program variables were the condenser liquid flow rate and scrubber pressure drop. The condenser liquid flow rate affected the amount of cooling in the condenser and, therefore, the condensation ratio. The scrubber pressure drop could be varied by changing the scrubber-throat flow area and the scrubber liquid-to-gas ratio.

Samples were usually taken at the condenser inlet and the scrubber outlet.

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For some runs, samples were also taken at the scrubber inlet. Sampling at three locations allowed the condenser and scrubber performance to be evaluated separately.

The particle size distribution and mass concentration were measured with University of Washington cascade impactors equipped with precutters. Several modified EPA Method 5 total filter runs were made to determine total mass concentration for compliance tests and to confirm impactor mass loadings.

From measurements of cumulative mass concentration as a function of particle size, particle penetration was computed as a function of particle size. The data was analyzed using a computer program which calculated impactor cut points and cumulative mass concentrations based on weight gain per stage, impactor flow rate, and impactor calibration data.

Performance Model

The system performance model can be used to predict the emission from a F/C scrubber system installed on a pollutant source with a known particle concentration and size distribution. The model allows independent variation of condensation ratio and scrubber pressure drop.

Without going into details of the mathematical model, the basic concepts and outline of the approach are discussed. The gas leaving the source is hot and has a water vapor content which depends on the source process. The first step is to saturate the gas by quenching it with water.

In the condenser there is diffusiophoretic and thermophoretic deposition, some inertial impaction, and (perhaps) Brownian diffusion. The particles in the gas leaving the condenser will have grown in mass due to the layer of water they carry.

Subsequent scrubbing of the gas will result in more particle collection by inertial impaction. There may be additional condensation, depending on water and gas temperatures, and its effects can be accounted for.

The mathematical model for the F/C demonstration plant accounts for the mechanisms and assumptions outlined below.

Saturator

1. Gas is humidified and cooled to adiabatic saturation temperature.
2. No condensation occurs.
3. Particle collection in the saturator is negligible.

Condenser

1. Particles are collected by impaction in packed column.
2. Condensation occurs, causing growth of particles.
3. Collection occurs in condenser due to diffusiophoresis.

Scrubber

1. Grown particles are collected by impaction in scrubber.
2. Negligible condensation occurs.

Experimental Results

Experimental performance measurements, made during the last 2 months of the testing, represent the best level attained after system adjustment was nearly completed. The "36 series" of runs were in the I.D. mode.

Runs 36/12 and following were made after a foaming problem was resolved and the scrubber liquid piping revised to better purge the internal sump. The "37 series" of runs were made in the F.D. mode, except for 37/21 and following, which were in the I.D. mode.

The hot gas temperature leaving the afterburner was, for most of the runs, significantly lower than anticipated. The design-basis hot gas temperature was 1,000°C, as measured in preliminary tests. The maximum temperature measured was about 850°C. The low gas temperature reduced the attainable condensation ratio: The maximum was about 0.2 g H_2O/g D.G. (dry gas). It had been anticipated that a condensation ratio of 0.3 g H_2O/g D.G. could be achieved with the higher gas temperature.

Particle Mass and Size

The average particle mass concentration at the condenser inlet was 2.4 g/DNm³ (33 percent higher than the design basis mass concentration of 1.8 g/DNm³).

Condenser inlet mass concentration measurements varied significantly from run to run reflecting the problem of having to sample during various periods in the charging cycle. Inlet sampling times had to be much shorter than outlets because the inlet concentrations were so high. Consequently, one inlet sample would not be representative of the period over which the outlet sample was taken. Computations of scrubber penetrations, on the basis of inlet and outlet samples for each run, varied greatly and randomly. To cope with this variation, an average condenser inlet size distribution was used in determining grade penetration curves.

The average cumulative mass inlet concentration distribution was used in combination with the cumulative mass outlet concentration distribution for each run to compute the grade penetration relationship for that run. Figures 2

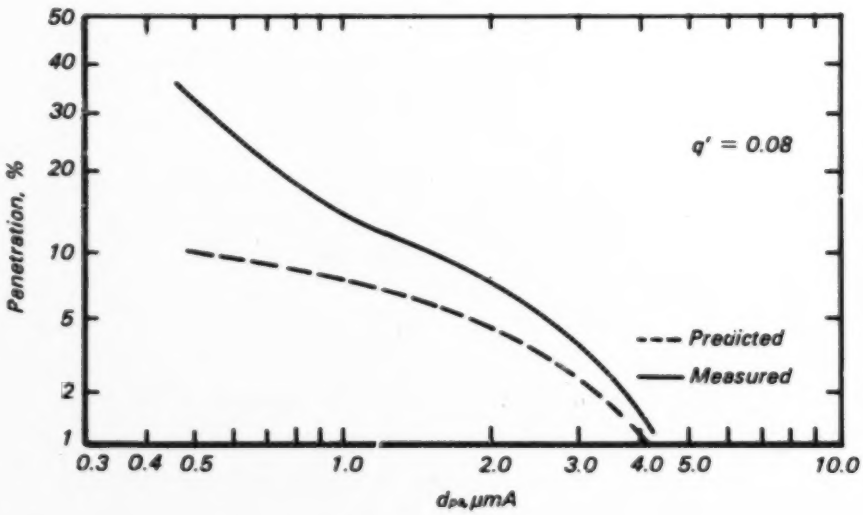

Figure 2. Particle penetration, Run 36/10.

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through 5 present experimental and predicted grade penetration curves for runs 36/10 through 36/13.

The grade penetration curves show that predictions and experiment compare well in some cases but not in others. Experimental penetrations at around 1μmA tend to be higher than predictions, at both F/C and non-F/C conditions.

The performance in the F.D. mode was erratic and not improved as much by condensation as it was in the I.D. mode. Some of the condensed water may have evaporated in the fan so that the particles entering the scrubber were smaller than those entering the fan. This question could not be resolved during the test.

The variation of computed penetrations appears to be caused by the uncertainty of the inlet size distribution. The agreement between predictions and experiment for many of the series-36 runs is considered good for field experimental conditions, where the equipment is being modified and the source process is cyclic.

Economic Analysis

An optimum F/C scrubber system design for this application would not be significantly different from the demonstration plant, and the process design would remain substantially unchanged. Major modifications recommended for an optimum system involve equipment redesign and specifications to reduce capital expense and to ensure that the gas temperature would be high.

Significant cost savings can be achieved by using a single combined condenser/scrubber vessel. Experiments with the demonstration plant showed that the vessel diameter and the packing depth can be smaller than used.

Because of space requirements, the cooling tower was on a platform, above the saturator and sump. Consequently, the most compact tower was chosen, not the most economical or energy efficient. A woodfilled cooling tower would have been the best choice if space had not been at a premium. Such a tower would require only 22 kW (30 hp), compared to 44 kW for the tower used on the demonstration plant. The wood packing may have some advantage over epoxy-coated steel for corrosion resistance. A second circulating water pump would be required for the system, but the total cost would be less because an expensive structural steel platform would not be needed.

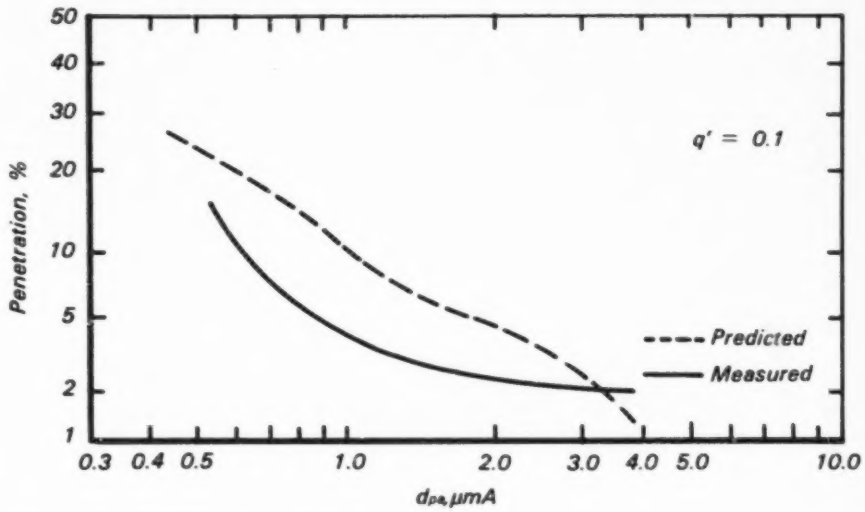

Figure 3. Particle penetration, Run 36/10.

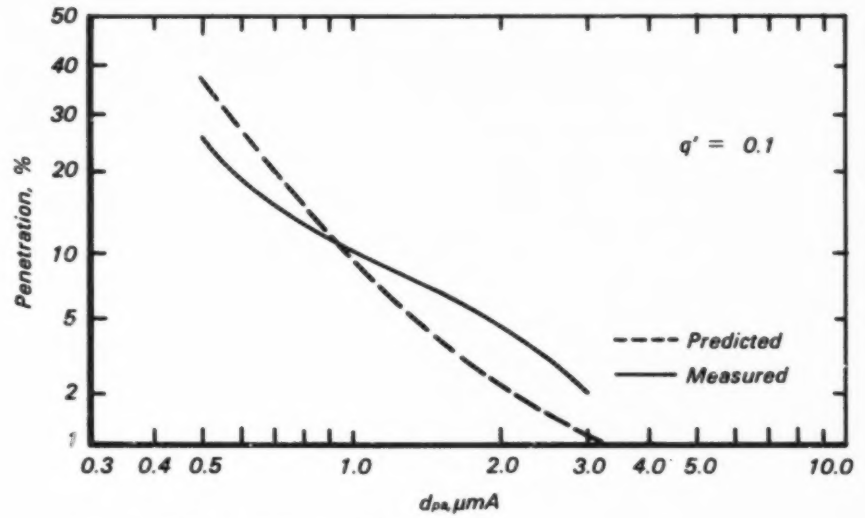

Figure 4. Paricle penetration, Run 36/12.

The saturator, designed to fit into space available at the foundry, would be smaller in an optimum system. The settler used on the demonstration system provided acceptable performance; however, the condenser, scrubber, and sump all were subject to deposition of sandy material which required frequent removal. Sloped bottoms should be used in all of these vessels.

It is also recommended that a moving-belt filter be used instead of the gravity settler to remove this sandy material. This would cost less than the settler used on the demonstration plant.

To evaluate the potential benefits of an F/C scrubber system (compared to a conventional one), the costs for a venturi scrubber system were estimated. The process conditions and emission criteria were the same for both systems.

Capital Cost Estimates

The capital cost of an optimum F/C system would consist of direct costs for delivered major equipment and other

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items (e.g., installation, piping, and electrical), as well as indirect cost (e.g., engineering, construction overhead, and contingencies). Table 2 shows the estimated direct and indirect costs for the F/C system and the high energy scrubber. All costs were adjusted to December 1979, using the Marshall and Stevens cost index.

Operating Costs

The operating cost of the air pollution control system consists of the annual cost of the utilities (power and water), raw material, and maintenance. Table 3 shows the power requirement for both the F/C scrubber system and a conventional scrubber. The F/C scrubber system would require only 65 percent of the power of the conventional scrubber. The exhaust fan for the conventional scrubber would require more than twice the power of that for the F/C system.

The estimated total operating costs are summarized in Table 4. The total operating cost for the F/C scrubber system was $131,230, compared to $150,300 for the conventional scrubber. The annual operating cost of the F/C scrubber system would be about $19,100 less than the cost for a conventional scrubber for the conditions stated. If the operating time were reduced below 4,000 hr/yr, the F/C system would be less favorable; however, longer operating time would make it more favorable. Power cost will also have an obvious effect on economics.

Conclusions

The following conclusions can be drawn from this study.

1. The performance data were in general accord with predictions based on design methods developed by A.P.T. on previous EPA contracts.
2. The F/C scrubber system was capable of complying with all applicable air pollution regulations for the site.
3. The F/C scrubber system needs only about 65 percent of the predicted power requirement of a conventional high energy scrubber to achieve the same performance.
4. The particle mass concentration and size distribution emitted during the cupola charging cycle varied greatly. Continuous or semi-continuous cupola charging with a conveyor system would

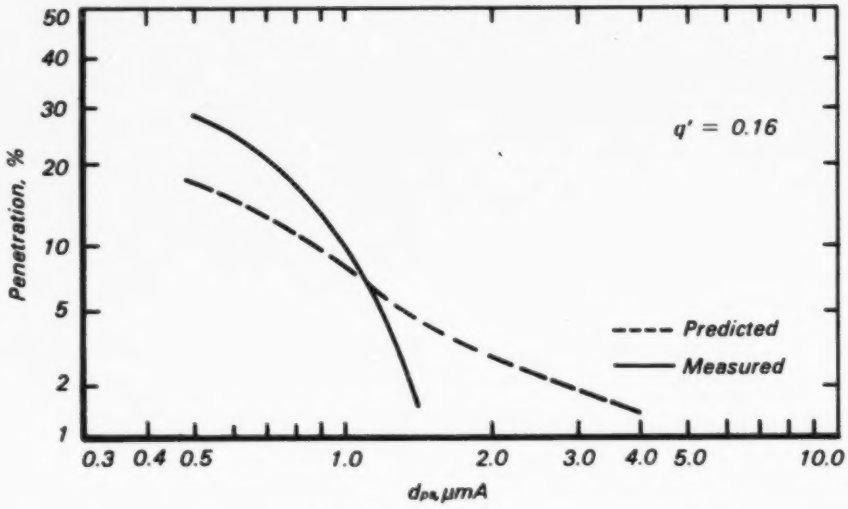

Figure 5. Particle penetration, Run 36/13.

Table 2. Direct and Indirect Costs

Item	F/C System		Conventional Scrubber	
	Ratio	Cost, $	Ratio	Cost, $
Direct				
Equipment	1.00	$102,380	1.00	$73,765
Installation	0.40	40,952	0.40	29,506
Instruments	0.10	10,238	0.10	7,377
Piping and Ducting	0.40	40,952	0.40	29,506
Electrical	0.10	10,238	0.10	7,377
Site Preparation	0.05	5,119	0.05	3,687
Total Direct Costs	2.05	$209,879	2.05	$151,218
Indirect				
Engineering	0.40	40,952	0.40	29,506
Construction Overhead	0.45	46,071	0.45	33,193
Contractor's Fee	0.10	10,238	0.10	7,377
Contingency	0.40	40,952	0.40	29,506
Total Indirect Costs	1.35	$138,213	1.35	$99,582
Fixed Capital Investment	3.40	$348,092	3.40	$250,800

Table 3. Summary of Power Requirements

Item	Power, kW (hp)	
	F/C Scrubber	Conventional Scrubber
Exhaust Fan	156 (210)	332 (445)
Saturator Pump	10 (13)	10 (13)
Scrubber Pump	2 (2)	3 (4)
Cooling Water Pumps	33 (44)	—
Cooling Tower Fan	22 (30)	—
Total Power Required	223 (299)	345 (462)

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probably reduce the variation in emissions and gas temperature.

5. The solid/liquid separation presented some maintenance problems. Additional attention should be given to equipment design, both to prevent settling in the scrubber equipment and to improve solids separation in the water treatment system.
6. Corrosion of the cooling tower packing was severe. Acids must be neutralized to prevent significant deterioration of steel components in the system. Maintenance of the proper circulating water pH is also important if stainless steel materials are used, because of the chloride content present.
7. Operation over 6 months showed that the F/C system can perform well and without significant difficulty under the demanding conditions of a ferrous foundry. During the entire test period, the F/C scrubbing system did not cause any production stoppages.
8. F/C scrubbing becomes more economically advantageous than conventional scrubbing as either power cost or plant operating time increases.

Recommendations

Demonstration plant experience has led to several recommendations on equipment changes; most of them are discussed above under "Economic Analysis." Essentially, the recommendations:

1. Minimize costs of equipment required to obtain F/C effects.
2. Maximize cupola flue gas temperature.
3. Provide adequate solids removal capacity for the scrubbing-liquid recycle stream.

Table 4. Summary of Estimated Annual Operating Costs

Item	Unit Cost	F/C Scrubber System	Conventional Scrubber
Capital Cost	@ 10% of F.C.I.[a]	$ 34,810	$ 25,080
Maintenance	Materials @ 3% of F.C.I.	10,440	7,520
	Labor @ 8 hr/wk shift, $9/hr	7,200	7,200
Operating Labor	@ 12 hr/wk shift, $9/hr	10,800	10,800
Power Cost[b]	$0.065/kWh	57,980	89,700
Water Use	$0.035/1,000 liters	2,000	2,000
Raw Materials	Soda ash $0.265/kg; flocculant $1.15/liter	8,000	8,000
Total Operating Cost		$131,230	$150,300

[a] Fixed capital investment.
[b] Estimated for 4,000 hr/yr.

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The complete report, entitled "Flux Force/Condensation Scrubbing for Collecting Fine Particulate from Iron Melting Cupolas," (Order No. PB 82-196 866; Cost: $13.50, subject to change) will be available only from:
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